

Geophysical Research

Earth's Electrical Conductivity as Viewed from the Laboratory

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Electrical conductivity of the deep Earth has been a topic of study since Lahiri and Price's initial study of 1939, which started with applying geomagnetic variations to look down into the mantle. Such geophysical pictures provide information that is needed for understanding the boundary conditions affecting the geodynamo, magnetic propagation outward from the core, core-mantle coupling, and changes in the length of day. Using earlier techniques in original ways, we constructed for the first time a laboratory-based, conductivity-depth profile for the entire mantle. Electrical conductivity of the Earth's mantle is influenced by many factors, including temperature, pressure, the coexistence of multiple mineral phases, and oxygen fugacity. We used recent laboratory measurements of electrical conductivity of mantle minerals in forward calculations of mantle conditions of temperature and pressure. In order to treat these factors and estimate the resulting uncertainties, we used several spatial averaging schemes for mixtures of the mantle minerals and have incorporated the effects of oxygen fugacity. Because the effective medium average lies between the Hashin-Shtrikman bounds in the whole mantle, we chose it as the preferred scheme to construct this laboratory-based conductivity-depth profile for the entire mantle. We confirmed our method by comparing apparent resistivities calculated from the laboratory-based conductivity profile with those from field geophysical models; results from the two approaches agree well.

Seismic Modeling Projects

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Seismic wave propagation modeling is an important tool for understanding wave-field phenomena and how it relates to observations of recorded seismic data. This type of modeling provides us with insight into important problems such as why certain regions of a petroleum reservoir are more difficult to image than others and why earthquake shaking in some regions is different from that in other regions.

Our seismic modeling work is being done in three areas: (1) developing fast numerical methods for modeling wave propagation in the forward propagation direction, (2) understanding the effects of scattering on the observed seismic data, and (3) developing and testing a novel wave-propagation method using a lattice-Boltzmann-type approach. The effort in (1) is a spin-off of our seismic migration effort, since seismic migration is basically seismic modeling with time running backwards. The methods we are developing are based on the solution on the one-way parabolic wave equation. They are substantially faster than other numerical methods for modeling wave propagation but are limited in that reverberations are not taken into account. They are appropriate for modeling some portions of seismic wave fields: those dominated by forward scattering. One example of such a wave field is the *L_g* portion of regional seismograms. In (2), we are investigating the influences of modeling the Earth as a random medium and thus obtaining some statistical estimate of the shape of observed seismograms. Such an approach is useful for understanding some portions of observed seismograms (coda) and for helping to understand the influences of scattering on observed seismic attenuation. Area (3) involves development of methods similar to those used in fluid-flow modeling based on a lattice-Boltzmann approach but focused on seismic wave propagation. We have developed two modeling methods using two different collision rules. These approaches have advantages over other modeling methods in that they can reliably model wave propagation in strongly heterogeneous media and they can reliably model the effects of a rough free surface, like the surface of the Earth.

Seismic Modeling Projects

We have found that the one-way propagation method is a reliable method for modeling regional seismograms in cases where forward scattering dominates. We have compared seismograms calculated using the one-way approach with those calculated using finite-difference modeling and found they are almost identical. However, the one-way approach requires about 100 times less computer time than the conventional finite-difference solution of the full wave equation.

We have performed numerical modeling of wave propagation using two-dimensional random media to investigate the effects of scattering on seismograms recorded at both local and regional distances. Numerical modeling techniques include finite difference solutions of the scalar (constant density) wave equation and a dual-domain (space-wave number) method for solving the one-way wave equation. We investigate wave propagation through media having Gaussian autocorrelation functions whose characteristic scale is much longer than the seismic wavelength. This high-frequency range is similar to the regime in which ray theory is appropriate for predicting travel times. In this case, our results are well predicted by models that include only forward scattering: waveforms are simple near the source and broaden with increasing source-receiver separation caused mainly by diffraction. Near the source, seismograms consist of a single pulse whose shape is that of the source pulse. There is no coda in the seismograms; after a packet of waves containing the first arrival and diffracted phases passes a given receiver, the trace amplitude goes to zero.

We also study media having autocorrelation functions with strong short wavelength heterogeneity. For example, we study propagation in media with both exponential and von Karman autocorrelation functions. For the case of the von Karman autocorrelation function with strong short-wavelength heterogeneity, we find that significant coda is generated. We can isolate the relative importance of backscattering and diffraction for these media by comparing seismograms calculated using the full wave equation with those calculated using a one-way wave equation approach, which does not model backscattering. Synthesized seismogram traces obtained from solution of the scalar wave equation contain continuous wave trains after the direct arrival, and it is not possible to isolate the source pulse in individual traces. However, stacking of synthesized traces calculated for multiple realizations of random media having the same characteristics shows that the source pulse can be isolated at short propagation distances. This coherence of the source pulse is consistent with predictions made by ray theory for stochastic media. For the case of media with strong short wavelength heterogeneity, we found that ensemble-average envelope traces, calculated by averaging envelopes calculated for several realizations of random media, are much smoother than those calculated for smoother media. This is presumably due to the strong averaging of many scattered wave pulses, which occurs in media where multiple scattering is important.

A Nonlinear Elastic Class of Materials

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Heterogeneous materials have a nonlinear elasticity that causes them to respond to strong sound signals with frequency shifts, harmonics, and modulation. Damage in homogeneous materials creates similar nonlinearities that can be used to detect such damage long before catastrophic failure. This project is discussed in detail in the Research Highlights section.

Nonlinear Wave Dynamics, Earthquake Strong Ground Motion and Infrastructure

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In addition to enormous human loss, the costs of the January 1995 Hanshin (Kobe) earthquake have been estimated to be 200 to 500 billion dollars. Approximately 150,000 buildings collapsed, and the Kobe port, the second largest in Japan, had to be closed. One might imagine the consequences of an earthquake of this magnitude striking Los Angeles. Earthquake damage is caused by strong ground motion, which is caused by seismic shear-wave amplification in relatively low-velocity sediments in the Earth's near surface, wave energy that couples into resonance modes of structures. If structure resonances are excited by strong ground motion, damage and/or failure will result. Strong ground motion has been responsible for the primary devastation associated with all large earthquakes in recent history—Mexico City, Anchorage, San Francisco, Northridge, and San Fernando.

Characterizing the near-surface sedimentary response to seismic waves responsible for creating strong ground motion is fundamental to developing predictive models, which form the basis for design of structures in earthquake prone regions. It is our conclusion that the most important aspect to unraveling and predicting the effects of strong ground motion on structures is study of the nonlinear behavior of the near-surface sediments. Nonlinearity of these materials controls the resonance modal frequencies and the wave amplitudes.

We propose that the most important local (site) effect on the frequency content of recorded waves in strong ground motion is an effect that has not previously been addressed, and we term this effect nonlinear frequency mixing (NFM) by transient feedback softening (TFS). TFS temporarily alters the velocity gradient of near-surface sediments when a high amplitude seismic wave is present. NFM appears simultaneously with TFS because of the local interaction between the spectral wave components in the sediments. The primary feature of NFM is the surprising and seemingly unpredictable appearance of frequency components for high-amplitude seismic waves, which cannot be explained by other means. We must be able to predict the appearance of these resonance frequencies in order to design earthquake resistant structures. We believe that in the future, we will be able to make such predictions using NFM.

Nonlinear Elasticity in Earth Materials

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Increasingly rapid progress is being made in the field of dynamic nonlinear elasticity of earth materials. Approximately 15 years ago, 3 groups of scientists (at Los Alamos, the Institute of Applied Physics in Russia, and the Institute of Physics of the Earth in Russia) independently initiated this research field. Today, dynamic nonlinear elasticity of Earth materials is well recognized in the domains of geomaterials, materials science, and strong ground motion, and there are an ever-increasing number of researchers in this area.

Rocks display unique elastic behavior. They are extremely nonlinear, hysteretic, possess discrete memory, and have slow dynamics (a long-term memory of strain). Although some of these types of nonlinearities may exist in other materials (for example, powdered metals) it is in rocks where these characteristics were first observed. It is now clear that rocks are part of a large class of materials that exhibit the same type of nonlinear behavior. The class of materials includes rock, damaged solids, and compressed powdered metals; we are finding other members of this class as we study additional materials. Furthermore, nonlinear behavior plays a central role in developing new methods with which to characterize material properties; some of these new methods include interrogating the elastic microstructure of rock, determining if a material is damaged, or monitoring progressive damage. Nonlinear attributes of rock have important consequences for processes in the earth such as earthquake strong ground motion, reservoir subsidence, seismic-wave propagation and attenuation, stress-fatigue damage, and hydraulic fracturing.

Nonlinear Elasticity in Earth Materials

We are developing a comprehensive theoretical and experimental framework that uses static and dynamic laboratory investigation of materials to provide a macroscopic and microscopic description of the elastic state. This framework also provides for turning the microscopic description into a prescription for material properties that can be used to predict change in stress state, both static and dynamic.

Nondestructive Testing of Materials

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Nonlinear wave methods for examining damage in materials may be thought of as the new frontier of acoustical nondestructive testing. These methods offer previously unimagined sensitivity, speed of application, and ease of interpretation. Strike a bell, and the bell rings at its resonance modes. Strike it harder and the bell rings at the same tone, only louder. Now imagine a small crack in the bell, perhaps invisible to the eye. We strike the bell gently, and it rings normally. Striking it harder we find, to our surprise, that the tone drops in frequency ever so slightly. Striking it even harder, the tone drops farther down in frequency. This frequency shift is a manifestation of the nonlinearity caused by the presence of the crack. This nonlinearity is an extremely sensitive indicator of the presence of damage. The undamaged portion of the sample produces a nearly zero nonlinear effect. The damaged portion of the material acts as a nonlinear mixer (multiplier). It is a localized effect. Using a frequency spectrum analysis, we can easily tell the difference between an undamaged and damaged object.

However, there is an even more sensitive, quicker, easy-to-apply method for detecting and examining material damage. We have found that measuring the nonlinear response of a sample provides a rapid, qualitative test of damage in numerous metal components such as alternator housings, engine bearing caps, some kinds of gears, Plexiglas, synthetic slates, weapons components, and other materials, when damage is localized. The elastic nonlinear response is also useful for examining the physical state of volumetrically damaged materials, such as concrete, rock core, and other porous materials. We are applying this technique to characterize dislocations in metals and to study progressive damage in these materials.